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Analytical modelling and laboratory studies of particle transport in filter media

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Analytical Modelling and Laboratory Studies of Particle Transport in Filter Media

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IN THE NAME OF GOD

AFFIRMATION

I hereby certify that the work presented in this thesis is original and has been carried out in the Department of Civil and Mining Engineering of the University of Wollongong and has not been submitted for any other degree.

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Fereydoon Vafai

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PUBLICATIONS THROUGH THIS STUDY

Indraratna, B., Vafai, F. and Dilema, E. (1996). Experimental study of filtration of lateritic clay slurry by sand filters. Proceeding of Inst. of Civil Eng. (Geotechnical Engineering). U.K, Vol. 119, No 2, pp 75-83.

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ABSTRACT

This study highlights an analytical model simulating the filtration phenomenon applicable to any base soil-filter system. Prior to development of such a model, different approaches in filter design criteria are reviewed, and their advantages and disadvantages are critically discussed. The mechanics of filtration are investigated both analytically and experimentally to achieve a better understanding of the behaviour of particle migration within the filter medium, and highlight the influencing parameters affecting the filtration process. The evaluation of pore size and coefficient of permeability of the filter are studied, and a new relationship is established to determine the coefficient of permeability based on finer fraction of particle size distribution curve (D_5 and D_{10}). Considering the theoretical concepts of filtration phenomenon, the proposed model include the actual hydraulic conditions and the relevant material properties such as: coefficient of permeability, porosity, friction angle, and the shape and distribution of particles. The model is founded on the concept of critical hydraulic gradient derived from limit equilibrium considerations, where the migration of particles is assumed to occur under applied hydraulic gradients exceeding this critical value. The rate of particle erosion, and hence, the filter effectiveness is quantified on the basis of mass and momentum conservation theories. By dividing the base soil and the filter domains into discrete elements, the model is capable of predicting the time-dependent particle gradation and permeability of each element, thereby the amount of material eroded from or retained within a given soil-filter system. Laboratory tests conducted on a fine base material verified the validity of the model. A design procedure for efficient filter using the

proposed model is presented in a separate chapter for two dimensional flow in a simplified earth structure. The model predictions are also compared with the commonly used empirical recommendations, including the conventional grading ratios. The response of the model in relation to the self-filtration phenomenon is also discussed. Finally, recommendations for further research are given in the context of the findings of this study.

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LIST OF SYMBOLS AND ABBREVIATIONS

D_h equivalent effective diameter

D_i average diameter in the i-th interval in particle size distribution curve

N number of particles;

G_i specific gravity of i-th particle;

γ_s unit weight of soil.

α shape coefficient of particle

d_a average pore diameter or average diameter of pore channel

d_{min} minimum diameter of the pore channel

d_{max} maximum diameter of the pore channel

V_p pore volume

V total volume of sample

n porosity

Δl length of of the sample in the flow direction

N' number of channels

$\Delta L'$ average length of the pore channels

T parameter of tortuosity

k coefficient of permeability (cm/sec or ft/day)

K intrinsic permeability factor (cm^2 or ft^2)

μ viscosity of permeant

e void ratio

k_T, k_{20} coefficient of permeability at T°C and 20°C respectively

η_T, η_{20} viscosity of liquid at T°C and 20°C respectively

γ unit weight of permeant

S specific surface = $\dfrac{6}{\sqrt{d_1/d_2}}$. d_1, d_2 = maximum and minimum sized particles

f angularity factor for rounded grains

$k_{0.85}$ coefficient of permeability at a void ratio of 0.85.

r^2 regression coefficient, decreases).

Q discharge capacity

Δh head loss through each layer,

H total head loss

R hydraulic radius

C correction factor for coefficient of permeability in turbulent flow

k' effective coefficient of permeability

i actual hydraulic gradient.

$\gamma_s h_s - \gamma_w h_w$ effective vertical stress

h_s height of soil layer above the element

γ_w unit weight of water

h_w height of water above the element

σ_x , σ_y lateral stress

σ_z vertical stress

λ constant factor

ϕ' effective friction angle of the material

W weight of the particle

F_u uplift force

ΔP net hydrodynamic force

ρ_m density of slurry

ρ_w , ρ_s density of water and soil grains, respectively

V_w volume of water in each element, and

V_s summation of the volume soil particles of which the diameter is smaller than d_{min}.

A cross section of the element

u average velocity of slurry entering element.

Δt time interval

Σ F summation of external forces,

V_m volume of the slurry in each element,

dz width of element in the flow direction.

g gravity acceleration

R viscous drag per unit mass of slurry

Q effluent flow rate

V_{out} volume of effluent

$V_{s_{out}}$ volume of soil eroded from element

$V_{w_{out}}$ volume of water coming out of element

P_j net volume of soil corresponding to a specific diameter j divided by the total volume of soil in that element (V_s), and Cumulative value of P_j is unity.

PSD particle size distribution of the soil

V_w volume of water in element

V_T total volume of element

D_{50} particle size in filter for which 50% by weight of particles are smaller

d_{50} particle size in base for which 50% by weight of particles are smaller

D_{15} particle size in filter for which 15% by weight of particles are smaller

d_{15} particle size in base for which 15% by weight of particles are smaller

d_{85} particle size in base for which 85% by weight of particles are smaller

k_x coefficient of permeability in X direction

k_z coefficient of permeability in Z direction

h water pressure head

Δx length of element in X direction

Δz length of element in Z direction

k_e equivalent coefficient of permeability of the system,

Δl_m length of m^{th} element,

k_m coefficient of permeability of m^{th} element, and

L $\Sigma \Delta l$.

F_y force resulting due to the lateral stress, σ_y

F_g effective weight

F_f friction force between the particle and flow channel boundary

ΔP net hydrodynamic force

i_α mean hydraulic gradient acting within element in α direction

i_x mean hydraulic gradient for horizontal seepage

$(i_x)_{cr}$ critical hydraulic gradient for horizontal seepage

R' hydrodynamic number

ν kinematics viscosity coefficient